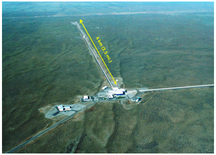
The Astrophysics of BH-BH mergers



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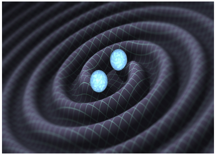

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– BH-BH mergers: previous models

– BH-BH mergers: revisions/new models

– BH-BH detections/non-detections: astrophysical implications

very biased and personal perspective...

Historical outline, gravitational-waves, sources

- 1915: Albert Einstein – General Relativity Theory
- 2005: LIGO & Virgo – construction of GW detectors
- 2005–2010: LIGO/Virgo – initial observations (18 Mpc)
- 2010–2015: LIGO/Virgo – upgrades
- Sep 2015–Jan 2016: LIGO – observations (70 Mpc)
- 2016–2018: LIGO/Virgo – upgrades/observations
- 2018–2028: LIGO/Virgo – advanced observations (200 Mpc)

- GW sources: NS-NS, BH-NS, BH-BH mergers
- NS-NS: 10 known (radio-pulsars) since 1970-ies: best candidate
- predictions: let's start in 2010... (before: only simple estimates)

Initial BH-BH predictions

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THE EFFECT OF METALLICITY ON THE DETECTION PROSPECTS FOR GRAVITATIONAL WAVES

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ABSTRACT

Data from the Sloan Digital Sky Survey (~300,000 galaxies) indicate that recent star formation (within the last 1 billion years) is bimodal: half of the stars form from gas with high amounts of metals (solar metallicity) and the other half form with small contribution of elements heavier than helium (~10%–30% solar). Theoretical studies of mass loss from the brightest stars derive significantly higher stellar-origin black hole (BH) masses (~30–80 $M_\odot$) than previously estimated for sub-solar compositions. We combine these findings to estimate the probability of detecting gravitational waves (GWs) arising from the inspiral of double compact objects. Our results show that a low-metallicity environment significantly boosts the formation of double compact object binaries with at least one BH. In particular, we find the GW detection rate is increased by a factor of 20 if the metallicity is decreased from solar (as in all previous estimates) to a 50–50 mixture of solar and 10% solar metallicity. The current sensitivity of the two largest instruments to neutron star–neutron star (NS–NS) binary inspirals (VIRGO: ~9 Mpc; LIGO: ~18) is not high enough to ensure a first detection. However, our results indicate that if a future instrument increased the sensitivity to ~50–100 Mpc, a detection of GWs would be expected within the first year of observation. It was previously thought that NS–NS inspirals were the most likely source for GW detection. Our results indicate that BH–BH binaries are ~25 times more likely sources than NS–NS systems and that we are on the cusp of GW detection.

Key words: binaries: close – gravitation – stars: evolution – stars: neutron

most likely detection: BH-BH merger (with mass up to $M_{\rm tot} = 70\ {\rm M}_\odot$)

Predictions: BH-BH merger rates and masses

Evolutionary assumptions and uncertainties:

- global properties: cosmology, SFR(z), $Z(z)$, IMF(z?)
- initial conditions: $a_{\rm orb}$, e, q, $f_{\rm binary}$, $V_{\rm rot}$

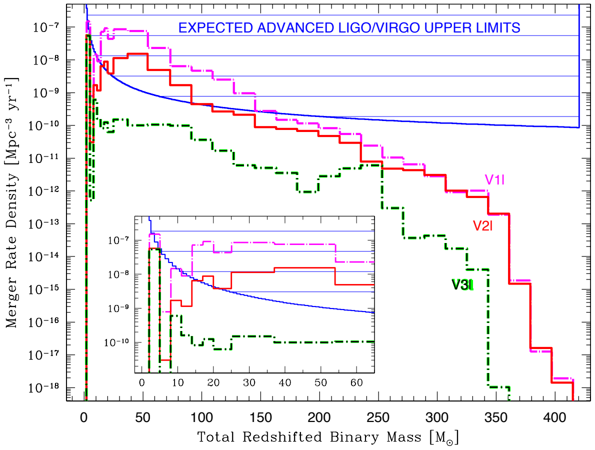
- single star evolution: winds + mixing –> radius & BH mass?
- binary CE evolution: development criteria + survival?

- BH formation: SN or Direct BH –> BH mass?
- BH formation: BH natal kicks –> low or high?

NS-NS/BH-NS/BH-BH masses & predicted rates vs aLIGO/Virgo upper limits ->

Advanced LIGO/Virgo upper limits: OLD OLD OLD

Dominik et al. 2013, 2015 –> Belczynski et al. 2015 (arXiv:1510.04615)



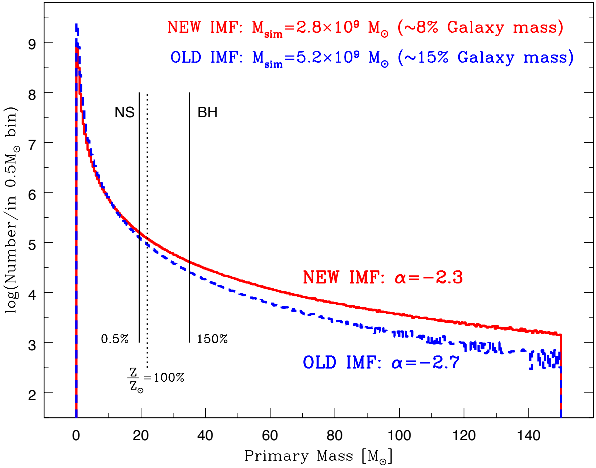
most likely detection: BH-BH merger with total redshifted mass 25–73 $M_\odot$

Overall updates (2010-2015): 1/5

Most important recent model updates:

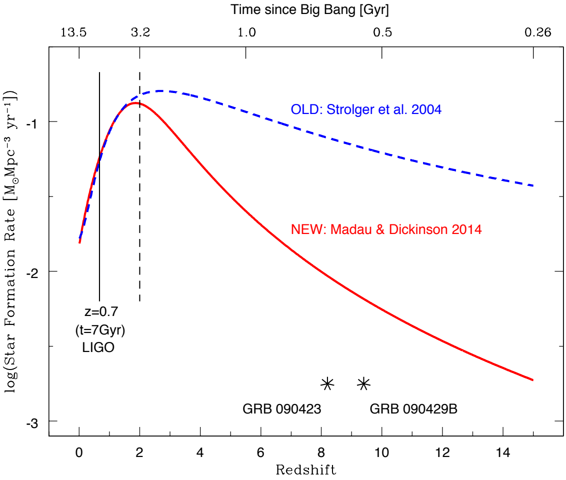
- low metallicity introduced: $Z_\odot$ -> 10% $Z_\odot$ -> 1% $Z_\odot$ (2010)
- binary CE evolution: more physical (2012)
- NS/BH formation: updated models (2012)
- first metallicity grid: 11 grid points (150% $Z_\odot$–0.5% $Z_\odot$) (2013)
- BH natal kicks: low and high (2015)
- initial conditions: $a_{\rm orb}$, e, $f_{\rm binary}$ (2015, now)
- global properties: IMF, SFR(z), Z(z) (now)
- metallicity grid: 32 grid points (150% $Z_\odot$–0.5% $Z_\odot$) (now)
- statistics: Monte Carlo (2 millions -> 20 millions) (now)

Initial mass function update: 2/5



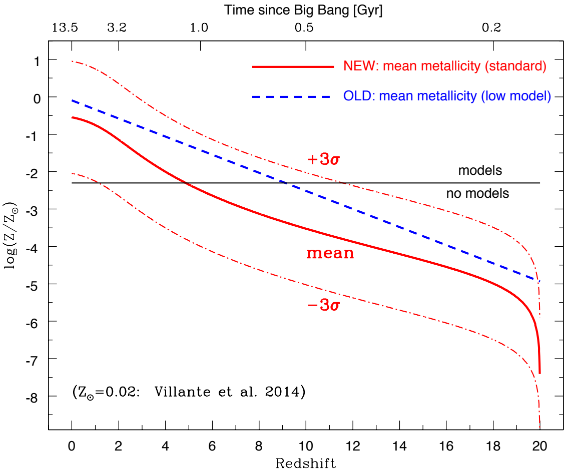
revised IMF: merger rate increase (de Mink & Belczynski 2015)

Star formation rate update: 3/5



revised SFR: merger rate decrease

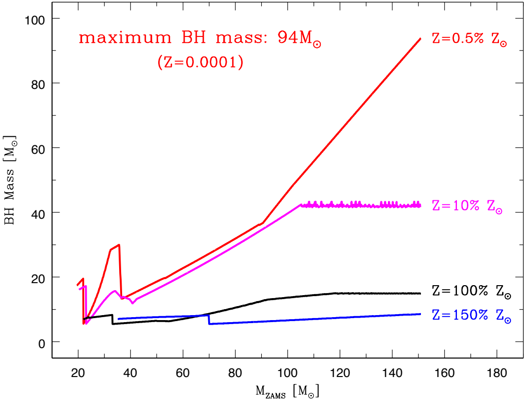
Metallicity evolution update: 4/5



revised metallicity: merger rate increase

Maximum BH mass: 5/5

Belczynski et al. 2010 (ApJ 714, 1217)



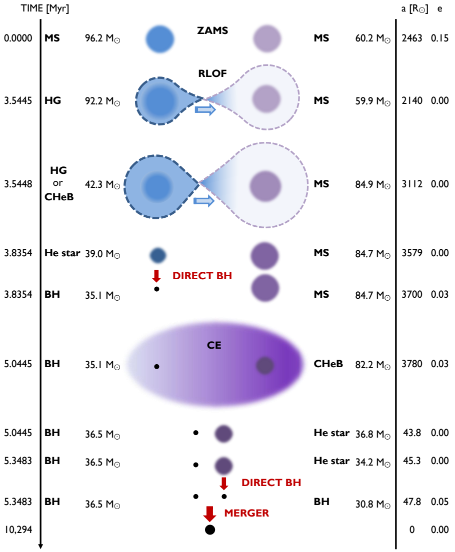
two potential updates:

stellar models: $\sim$ 130 $M_\odot$
(Spera et al. 2015)

IMF extension: $\sim$ 300 $M_\odot$
(Belczynski et al. 2014)

stellar origin BH can reach: $\sim$ 100 $M_\odot$

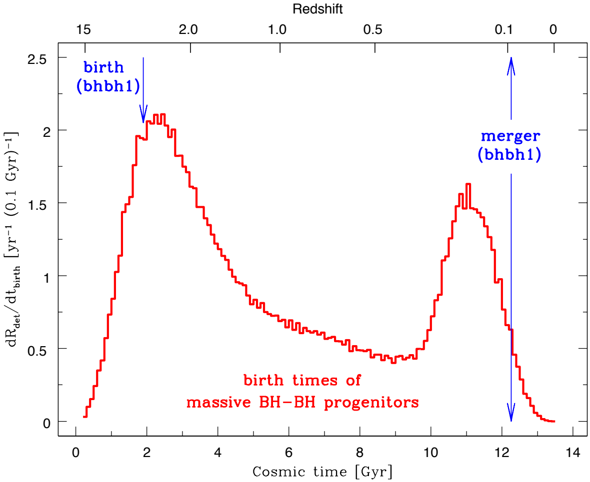
Formation of massive BH-BH merger



- low metallicity: $Z < 10\% \, Z_\odot$
- CE: tested with MESA
  credit: Pablo Marchant (Bonn)
- merger with delay: 10 Gyr
- O1 horizon: $z = 0.7$ (inspiral-merger-ringdown)
- total merger mass: 25–73 $\mathrm{M}_\odot$
- aligned BH spins: tilt$=$ 0 deg
- BH spin: $a = 0.0$ -> $a = 0.126$
  $a = 0.5$ -> $a = 0.572$
  $a = 0.9$ -> $a = 0.920$

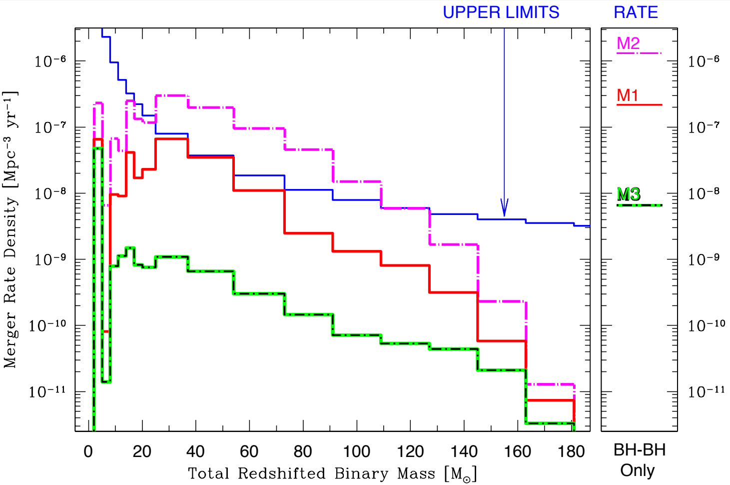
credit: Wojciech Gladysz (Warsaw)

BH-BH progenitors: birth times



typical BH-BH progenitors: very old systems 10 Gyr

Astro implications: rate prediction

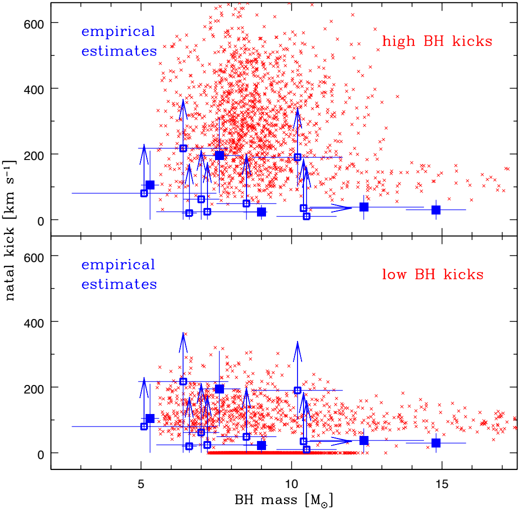


expected BH-BH detection rate for standard (M1) model: $\sim$ 5 month^{-1}

Astro implications: if BH-BH mergers detected

- BH-BH merger: dominant GW source (field evolution)
- BH-BH progenitor: from distant past and low Z environ
- BH-BH merger: comparable masses, aligned (?) birth spins
- EM Observations: supported by IC10 X-1 and NGC300 X-1
- high BH kicks: most likely excluded if any detections
- easy common envelope: excluded if only few detections
- field detection rates: 5$\times$ higher than for dynamical BH-BH
  (Belczynski et al. 2015 versus Rodriguez et al. 2015)

BH natal kicks: extras 1/4



EM observations:

no good information

if BH kicks decrease with M_{BH}:

- asymmetric mass ejection
- asymmetric neutrino emission

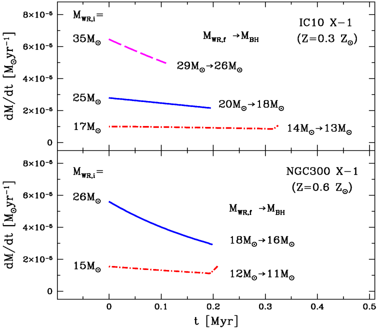
both mechanisms: OK!

Belczynski et al. 2015 (arXiv:1510.04615)

Observations (Tomek Bulik): 1/3

The interesting case of IC10 X-1 and NGC300X-1

- WR stars – mass ~30 solar masses
- Compact objects – ~ 20-30 solar masses (but see later)
- Orbital period ~ 1.25 days
- Future evolution: mass transfer, mass loss, formation of 2nd BH
- Formation of BH-BH with the coalescence time ~a few Gyrs
- Low metallicity host galaxies



Bulik, Belczynski, Prestwich 2011

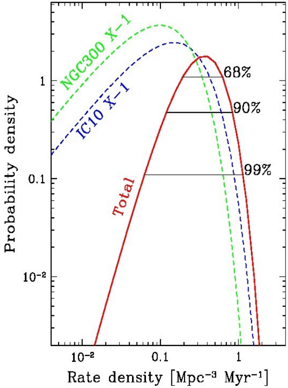
Observations (Tomek Bulik): 2/3

Rate density estimate

- Estimate of the observability volume and object density
- Estimate of the time to coalescence
- Just two objects – low stastistic leads to high uncertainty
- Rate density very high
- Expected to be close to detection even with Initial LIGO/VIRGO
- Expected component mass range:

  ~20-40 solar mass
- Expected total mass:

  ~60 solar masses



Bulik, Belczynski, Prestwich 2011

Observations (Tomek Bulik): 3/3

Potential problem with mass estimate

- Recent mesurement of the X-ray eclipse over the optical lightcurve (Laycock et al. 2015)
- Offset of 0.25 in phase
- The radial velocity has a contribution from ionized wind velocity
- Imply a possibilty that the companion is a low mass BH or a NS
- Model of Kerkwijk et al. (1996)

Potential problems:

Evolution: it is very difficult to form a massive WR star in a binary with a low mass compact object

Mass transfer: if wind, then the X-ray luminosity (10^{38} erg/s) is unusually high (too large by 2-3 orders of magnitude)

Mass transfer: if RLOF, then the system should not be stable.

It is still quite likely that the companions in IC10 X-1 and NGC300 X-1 are ~20 solar mass BHs

Birth time distribution for BH-BH progenitors